

On the Simultaneous Generation of High-energy Emission and Submillimeter/Infrared Radiation from Active Galactic Nuclei

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ABSTRACT

For active galactic nuclei (AGNs) we study the role of the mechanism of quasi-linear diffusion (QLD) in producing the high energy emission in the MeV-GeV domains strongly connected with the submillimeter/infrared radiation. Considering the kinetic equation governing the stationary regime of the QLD we investigate the feedback of the diffusion on electrons. We show that this process leads to the distribution of particles by the pitch angles, implying that the synchrotron mechanism is no longer prevented by energy losses. Examining a reasonable interval of physical parameters, we show that it is possible to produce MeV-GeV γ -rays, strongly correlated with submillimeter/infrared bands.

Subject headings: galaxies: active — gamma rays — submillimeter — infrared radiation

1. Introduction

According to the model of AGNs, cold material close to the central black hole forms an accretion disc, matter inside which due to the dissipative forces transports inwards causing the accretion disc to heat up. Such a hot material in turn can inverse-Compton scatter photons up to X-ray energies (Blandford et al. 1990). From high energy astronomical sources a special interest deserve blazar type AGNs the standard model of which implies the presence of the supermassive black hole, surrounded by the accretion disc and ejecting twin relativistic jets. The observationally evident broadband emission spectrum of blazars is made of two components: the low energy (from radio to optical) domain attributed to the synchrotron emission and the high energy (from X-rays to γ -rays) part formed by either the inverse-Compton mechanism (Blandford et al. 1990) or the curvature radiation (Gangadhara 1996; Thomas & Gangadhara 2005). A recent investigation of the parsec scale jets is very important. Giroletti et al. (2010) argued that the high energy and radio emissions are strongly correlated. Our model on the other hand, as we will see, automatically provides a connection

of radiation in high energy and radio domains. Magnetospheres of AGNs have strong magnetic fields, therefore, synchrotron cooling timescales are relatively short, leading to efficient energy losses. This in turn creates appropriate conditions for particles to transit to their ground Landau state. When this happens, relativistic electrons will move only along magnetic field lines without emitting in the synchrotron regime.

Despite the very strong magnetic field, which prevents a continuous process of the synchrotron emission, there is a possibility to overcome the dissipative factors and maintain the radiation mechanism. Machabeli & Usov (1979) have studied the cyclotron instability of two-component electron-positron plasma for the pulsar, NP 0532. It was found that the instability arises near the light cylinder surface (a hypothetical zone, where the linear velocity of rigid rotation equals exactly the speed of light) leading to a certain distribution of particles by pitch angles and the consequent synchrotron radiation. Lominadze et al. (1979) considered the magnetospheres of the pulsar NP 0532 and the Crab nebula, studying the generation of waves from optical to gamma-ray domains. The similar approach was presented by Malov & Machabeli (2001) where the QLD

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was applied to the radio pulsars. The authors found that the transverse momenta of relativistic particles induced by the cyclotron instability caused the stable non-zero pitch angle distribution maintained by means of the QLD. Analyzing the data obtained from MAGIC Cherenkov telescope between 2007 October and 2008 February (Aliu et al. 2008) we found that, the observed coincidence of signals in the optical and γ -ray domains are easily explained by the QLD process, which leads to the increase of the pitch angles, making the synchrotron process feasible (Machabeli & Osmanov 2009, 2010).

In the magnetospheres of AGNs the magnetic fields are of the order of $10^4 G$ (Thorne et al. 1988), close to the supermassive black hole, and $100 G - 300 G$ close to the light cylinder surface. Therefore, the aforementioned QLD mechanism could be of great importance for AGNs as well. For this purpose by considering the cyclotron instability excited in the radio domain, in (Osmanov & Machabeli 2010) we studied the quasi-linear interaction of proper modes of AGN magnetospheric plasmas with the resonant plasma particles investigating the QLD in the context of producing the soft and hard X-ray emission from AGNs. Under favorable conditions this mechanism could also be efficient for explaining the MeV-GeV energy synchrotron emission, strongly connected either with the submillimeter radio band, or with the infrared emission induced by the cyclotron instability. This will be the subject of the present paper, which is organized as follows. In Section 2 we describe our model, in Sect. 3 we apply the mechanism of QLD to AGNs and in Sect. 4 we summarize our results.

2. Main consideration

In general, AGN magnetospheres consist of relatively low energy particles and very high energy particles (electrons). Therefore, in the framework of the model we consider the plasma composed of two components: a) the so-called plasma component with the Lorentz factor, γ_p and b) the beam component with the Lorentz factor, γ_b ($\gamma_b \gg \gamma_p$). Such a system as was shown by (Kazbegi et al. 1992) undergoes the cyclotron instability induced by the Doppler effect with the following resonance

condition

$$\omega - k_{\parallel} V_{\parallel} - k_x u_x \pm \frac{\omega_B}{\gamma_b} = 0, \quad (1)$$

where k_{\parallel} is the longitudinal (parallel to the background magnetic field) component of the wave vector, k_x is the component along the drift, V_{\parallel} is the longitudinal component of plasma flow velocity, $u_x \equiv c V_{\parallel} \gamma_b / \rho \omega_B$ is the drift velocity of particles, c is the speed of light, ρ is field line's curvature radius, $\omega_B \equiv eB/mc$ is the cyclotron frequency, B is the magnetic induction and e and m are electron's charge and the rest mass, respectively. Positive sign corresponds to the damping of the excited modes, whereas the negative sign relates to the unstable mode. One can show that, when the aforementioned resonance takes place, the transverse waves with the dispersion relation

$$\omega_t \approx kc(1 - \delta), \quad \delta = \frac{\omega_p^2}{4\omega_B^2 \gamma_p^3}, \quad (2)$$

are induced. k is the modulus of the wave vector, $\omega_p \equiv \sqrt{4\pi n_p e^2 / m}$ is the plasma frequency and n_p is the plasma density. From Eqs. (1,2) is clear that the excited cyclotron frequency is given by (Malov & Machabeli 2001)

$$\omega \approx \frac{\omega_B}{\delta \cdot \gamma_b}. \quad (3)$$

In spite of the resonant character of the cyclotron modes, the corresponding frequency is not well peaked, because ω depends also on the Lorentz factors of the resonant (beam) particles, that do not have narrow energy spectra. It is worth noting that unlike the synchrotron mechanism ($\lambda < n_p^{-1/3}$), (λ is the wavelength), where radiation process can be described by a single particle approach, excitation of the aforementioned waves is a collective phenomenon ($\lambda > n_p^{-1/3}$), which in its turn is a direct consequence of one-dimensionality of the distribution function. On the other hand, such a behaviour of this function is guaranteed by the strong magnetic field that forces particles to move along the field lines.

By the first sentence after Eq. 3 we would like to note that despite the resonant character of the process, the corresponding frequency is not well peaked, because the frequency depends also on the Lorentz factor of the resonant particles, and the corresponding interval of γ_b -s is not narrow

In general, two dissipative factors lead to a decrease of the pitch angle. The force that provides conservation of adiabatic invariant $I = 3cp_\perp^2/2eB$ in non-uniform magnetic field (Landau & Lifshitz 1971) [see also (Osmanov & Machabeli 2010)]

$$G_\perp = -\frac{mc^2}{\rho}\gamma_b\psi, \quad G_\parallel = \frac{mc^2}{\rho}\gamma_b\psi^2 \quad (4)$$

and the radiation reaction force (Landau & Lifshitz 1971)

$$F_\perp = -\alpha\psi(1 + \gamma_b^2\psi^2), \quad F_\parallel = -\alpha\gamma_b^2\psi^2, \quad (5)$$

where $\alpha = 2e^2\omega_B^2/(3c^2)$ and ψ is the pitch angle. Only under the action of these forces the pitch angles tend to decrease, inevitably killing the synchrotron emission. In reality the situation is principally different, because the excited relatively low frequency waves (in our case submillimeter/infrared) by means of the cyclotron resonance leads to the QLD. Unlike the dissipative effects of (\mathbf{F}, \mathbf{G}) , diffusion creates non-zero distribution function with respect to pitch angles, and supports the synchrotron emission. It is clear that under favorable conditions the effect of quasi-linear diffusion may balance the dissipation, therefore, our objective is to find the distribution of particles by pitch angles, estimate their mean value and analyze the corresponding synchrotron emission energy. On the other hand, since the QLD results from the feedback of the cyclotron modes, apart from the high energy emission, the system will also be characterized by the low energy radiation.

In (Osmanov & Machabeli 2010) we studied the role of the QLD in producing the X-ray emission by means of ultra-relativistic electrons in AGN magnetospheric flows. It was shown that the cyclotron resonance provides emission in a low energy domain - radio band. Unlike the physical conditions ($|G_\perp| \gg |F_\perp|$ and $|G_\parallel| \ll |F_\parallel|$) considered in (Osmanov & Machabeli 2010), in the present paper we examine physically different regime, $|G_\perp| \ll |F_\perp|$ and $|G_\parallel| \ll |F_\parallel|$, which reduces the stationary kinetic equation governing the quasi-linear diffusion to (Malov & Machabeli 2001)

$$\frac{\partial}{\partial\psi}(\psi F_\perp f) = \frac{1}{mc\gamma_b} \frac{\partial}{\partial\psi} \left(\psi D_{\perp\perp} \frac{\partial f}{\partial\psi} \right), \quad (6)$$

where $f = f(\psi)$ is the distribution function of

particles and

$$D_{\perp\perp} \approx \frac{\pi^2 e^2}{m^2 c^3} \frac{\delta}{\gamma_b^2} |E_k|^2, \quad (7)$$

is the diffusion coefficient. $|E_k|^2$ is the energy density per unit wavelength, therefore the energy density of the cyclotron waves are of the order of $|E_k|^2 k$. We assume that $\sim 50\%$ of the resonant plasma energy, $mc^2 n_b \gamma_b$, converts to waves (Osmanov & Machabeli 2010), then for an expression of $|E_k|^2$ one obtains (Malov & Machabeli 2001)

$$|E_k|^2 = \frac{mc^3 n_b \gamma_b}{2\omega}. \quad (8)$$

The distribution function obtained from Eq. (7) is given by

$$f(\psi) = C e^{-A\psi^4}, \quad (9)$$

where

$$A \equiv \frac{\alpha mc \gamma_b^3}{4D_{\perp\perp}}, \quad C = \text{const.} \quad (10)$$

Unlike the work presented in (Osmanov & Machabeli 2010), due to the different regime, $f(\psi)$ behaves as $e^{-A\psi^4}$ instead of $e^{-A_1\psi^2}$ [see Eq. (11) in (Osmanov & Machabeli 2010)].

As we see, particles are distributed by the pitch angles, therefore, the electrons will emit via the synchrotron process without damping.

3. Discussion

In this section we apply the model of the QLD to the light cylinder lengthscales of typical AGNs.

For explaining the high energy radiation, it is strongly believed that AGN magnetospheres are consist of highly relativistic electrons. This fact sets another problem - how to accelerate these particles to such high energies? In general, there are several mechanisms, which may account for the efficient acceleration of electrons. Indeed, as is shown in a series of papers, Fermi-type acceleration process (Catanese & Weeks 1999), re-acceleration of electron-positron pairs as a feedback mechanism (Ghisellini et al. 1993) and centrifugal acceleration (Machabeli & Rogava 1994; Osmanov et al. 2007; Rieger & Aharonian 2008; Osmanov 2010) may provide very high Lorentz factors of the order of $\gamma_b \sim 10^{5-9}$. Therefore, in the framework of the paper an existence of such particles is assumed to be as a given fact. If

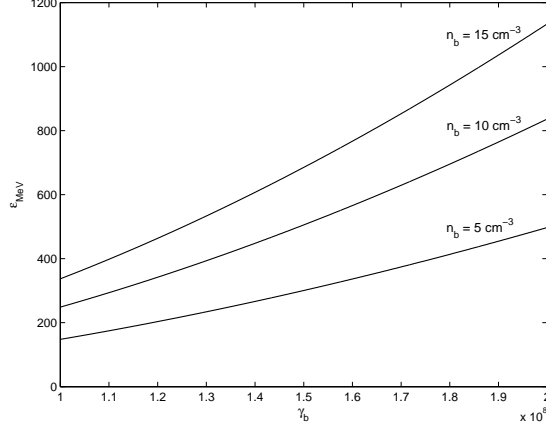


Fig. 1.— Behaviour of ϵ_{MeV} versus γ_b for different values of n_b . The set of parameters is $L = 10^{45} \text{ erg/s}$, $\Omega = 3 \times 10^{-5} \text{ rad/s}$, $\gamma_p = 200$ and $n_b = \{5; 10; 15\} \text{ cm}^{-3}$. As is seen from the plots, relativistic electrons with Lorentz factors $\gamma_b = \{1 - 2\} \times 10^8$ may provide the high energy radiation in the MeV-GeV domain.

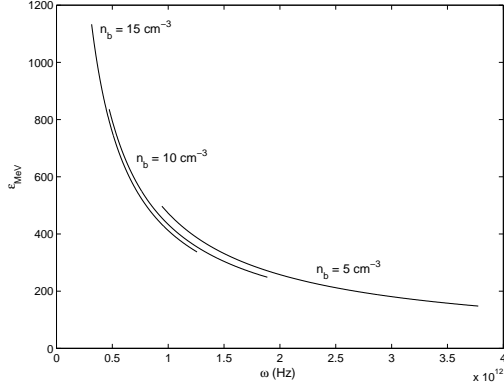


Fig. 2.— Behaviour of ϵ_{MeV} versus ω for different values of n_b . The set of parameters is $L = 10^{45} \text{ erg/s}$, $\Omega = 3 \times 10^{-5} \text{ rad/s}$, $\gamma_p = 200$ and $n_b = \{5; 10; 15\} \text{ cm}^{-3}$. We see that the high energy radiation is strongly connected with the submillimeter/low infrared emission.

we suppose an isotropic distribution of relativistic electrons, one can estimate the synchrotron cooling timescale (Osmanov & Machabeli 2010)

$$t_{cool} \approx 5 \times 10^{-3} \times \left(\frac{10^2 G}{B} \right)^2 \times \left(\frac{10^8}{\gamma} \right) s. \quad (11)$$

The value of the magnetic induction is given by (Osmanov & Machabeli 2010)

$$B_{lc} \approx 260 \times \left(\frac{L}{10^{45} \text{ erg/s}} \right)^{1/2} \times \left(\frac{\Omega}{3 \times 10^{-5} \text{ s}^{-1}} \right) G, \quad (12)$$

where L is the bolometric luminosity of the AGN and $r_{lc} = c/\Omega$ is the light cylinder radius (a hypothetical zone, where the linear velocity of rigid rotation exactly equals the speed of light). Ω is the magnetic field lines' angular velocity of rotation, normalized to the value $3 \times 10^{-5} \text{ s}^{-1}$ (Belvedere et al. 1989). Throughout the paper we assume that the magnetic field is robust enough to maintain the frozen-in condition in the magnetosphere of the AGN. Indeed, as one can see, for the typical magnetospheric parameters, $\gamma_b \sim 10^8$, $n_b \sim 10 \text{ cm}^{-3}$, the following condition $B_{lc}^2/8\pi > \gamma_b m n_b c^2$ is satisfied, which means that the plasma particles will be forced to follow the rigidly rotating field lines. During such a motion, especially on the light cylinder lengthscales, the electrons will undergo the centrifugal force accelerating them up to very high Lorentz factors $\sim 10^{8-9}$ (Osmanov et al. 2007; Rieger & Aharonian 2008)

It is clear from Eq. (11) that for a certain class of physical parameters the synchrotron cooling timescale is of the order of $5 \times 10^{-4} \text{ s}$. On the other hand, the kinematic timescale of the system, $t_{kin} \sim r_{lc}/c \sim 3 \times 10^4 \text{ s}$ is by many orders of magnitude bigger than t_{cool} , which in turn means that without the quasi-linear diffusion, particles very soon would stop emitting in the synchrotron regime, after transiting to their ground Landau level.

Kazbegi et al. (1992) showed that the anomalous Doppler effect generates the cyclotron waves with the frequency (Osmanov & Machabeli 2010)

$$\omega \approx 6.8 \times 10^9 \times \left(\frac{\gamma_p}{100} \right)^4 \times \left(\frac{10^8}{\gamma_b} \right)^2 \times \left(\frac{B}{100 G} \right)^3 \times \left(\frac{10 \text{ cm}^{-3}}{n_b} \right) \text{ Hz}, \quad (13)$$

leading to the process of the quasi-linear diffusion, which, despite the efficient dissipative factors, creates the pitch angles.

To demonstrate the present model, we consider an AGN with the bolometric luminosity $L = 10^{45} \text{erg/s}$. Let us examine the following parameters $\Omega = 3 \times 10^{-5} \text{rad/s}$, $\gamma_b = 10^8$ and $n_b = 10 \text{cm}^{-3}$. Since the particles are distributed by the pitch angles [see Eq. (9)], for analyzing the synchrotron emission it is reasonable to estimate a mean value of ψ

$$\bar{\psi} = \frac{\int_0^\infty \psi f(\psi) d\psi}{\int_0^\infty f(\psi) d\psi} \approx \frac{0.5}{\sqrt[4]{A}}. \quad (14)$$

Then one can show from Eq. (14) that for the aforementioned parameters the pitch angle is of the order of $8 \times 10^{-3} \text{rad}$, therefore, relativistic electrons will inevitably emit photons with energies (Rybicki & Lightman 1979)

$$\epsilon_{eV} \approx 1.2 \times 10^{-8} B \gamma^2 \sin \psi. \quad (15)$$

After substituting the value of $\bar{\psi}$ in Eq. (15), we see that the synchrotron emission generates radiation in the MeV domain.

The quasi-linear diffusion works if the cyclotron modes are excited, therefore, it is essential to estimate the timescale of the corresponding instability (t_{ins}) and compare it with the kinematic timescale of the system. According to the work of Kazbegi et al. (1992) the growth rate of the instability is given by

$$\Gamma = \pi \frac{\omega_b^2}{\omega \gamma_p} \quad \text{if} \quad \frac{1}{2} \frac{u_x^2}{c^2} \ll \delta \quad (16)$$

and

$$\Gamma = \pi \frac{\omega_b^2}{2\omega \gamma_p} \frac{u_x^2}{\delta \cdot c^2} \quad \text{if} \quad \frac{1}{2} \frac{u_x^2}{c^2} \gg \delta, \quad (17)$$

where $\omega_b \equiv \sqrt{4\pi n_b e^2/m}$ is the plasma frequency of beam electrons. It is easy to show that for $n_b = 10 \text{cm}^{-3}$, $\gamma_p = 200$ (see Fig. 1), $V_\parallel \sim c$ and $\rho \sim R_g$, one obtains $u_x^2/(2c^2) \ll 1$, implying that the increment of the instability is given by Eq. (16). The cyclotron resonance makes sense if $t_{ins}/t_{kin} < 1$, then, by taking into account the definition of the kinematic timescale, r_{lc}/c and the instability timescale, $1/\Gamma$, one can show that the

aforementioned condition reduces to

$$3.5 \times 10^{-3} \times \left(\frac{\gamma_p}{100}\right)^5 \times \left(\frac{10^8}{\gamma_b}\right)^2 \times \left(\frac{10 \text{cm}^{-3}}{n_b}\right)^2 < 1. \quad (18)$$

As is clear from Eq. (18), the condition is very sensitive to the Lorentz factor of the plasma components, and for relatively higher values of γ_p the condition will violate. The upper limit of γ_p , when the condition is still valid is of the order of 300 for $\gamma_b \sim 10^8$ and $n_b \sim 10 \text{cm}^{-3}$.

For studying the efficiency of the QLD, we examine the following set of the parameters $L = 10^{45} \text{erg/s}$, $\Omega = 3 \times 10^{-5} \text{rad/s}$, $\gamma_p = 200$ and $n_b = \{5; 10; 15\} \text{cm}^{-3}$ and the results are demonstrated in Fig.1 where we show the behaviour of ϵ_{MeV} versus γ_b . From the plots is clear that ϵ_{MeV} is a continuously increasing function of the beam Lorentz factor, which is a natural result of the fact that more energetic particles produce more energetic photons. The behaviour of ϵ_{MeV} versus n_b is different, more dense beam electrons produce photons with lower energies. This can be seen from Eqs. (10,14): $\bar{\psi} \sim \sqrt[4]{D_{\perp\perp}}$, which by combining with $D_{\perp\perp} \sim n_b^3$ [see Eqs. (7,8)] confirms the dependence $\epsilon_{MeV}(n_b)$. According to the results demonstrated in the figure, relativistic electrons with Lorentz factors $\gamma_b = \{1-2\} \times 10^8$ may provide the high energy radiation in the MeV-GeV domain.

Since the generation of the synchrotron emission strongly depends on the cyclotron waves, we also investigate the behaviour of ϵ_{MeV} versus ω . Figure 2 shows the function $\epsilon_{MeV}(\omega)$ for several values of n_b . The set of parameters is the same as in the previous figure. As is clear from the plots, the $\{200-1200\} \text{MeV}$ radiation is strongly connected with the submillimeter ($\sim [0.3-3] \times 10^{12} \text{Hz}$) and low infrared ($\sim [3-3.8] \times 10^{12} \text{Hz}$) emission.

Another important parameter, the physical system depends on, is the Lorentz factor of the plasma component. Therefore, it is reasonable to demonstrate the function $\epsilon_{MeV}(\omega)$ for different values of γ_p . These results are shown in Fig. 3, where the set of parameters is $L = 10^{45} \text{erg/s}$, $\Omega = 3 \times 10^{-5} \text{rad/s}$, $\gamma_p = \{200; 250; 300\}$ and $n_b = \{5; 10; 15\} \text{cm}^{-3}$. As we see, the excited infrared domain extends up to $\sim 10^{13} \text{Hz}$, which is strongly connected with high energy emission

(100 MeV). As is clear from the figure, higher values of γ_p correspond to lower synchrotron energies. Indeed, by taking into account the relation $\bar{\psi} \sim \sqrt[4]{D_{\perp\perp}}$ combined with Eqs. (7,8) one can see that $\psi \sim 1/\gamma_p^2$.

As is clear from the results, the quasi-linear diffusion together with the cyclotron instability may guarantee production of high energy radiation in the MeV-GeV domains strongly connected with submillimeter/infrared emission. The major difference in results from our previous work is that in (Osmanov & Machabeli 2010) we studied physical conditions leading to excitation of X-rays connected with the relatively low frequency radio band (KHz-MHz), whereas in the present paper both energies (produced as by synchrotron as by cyclotron mechanisms respectively) are much higher. This investigation sets another problem: since the QLD is a feasible mechanism providing the aforementioned high energies, one of the important next steps could be testing of MeV-GeV AGNs exhibiting an efficient submillimeter/infrared radiation and see if the strong correlation is observationally evident. This in turn, could be a certain test for estimating the AGN magnetospheric parameters, such as the density and the Lorentz factors of plasma component and beam electrons. A particular future objective is to investigate theoretically the radiative signatures of both high and low energy emissions respectively. This work we are going to perform sooner or later.

4. Summary

The main aspects of the present work can be summarized as follows:

1. Mechanisms producing strongly connected high and low energy radiation was studied by taking into account the QLD in the AGN magnetospheres. Considering a physical regime different from that of (Osmanov & Machabeli 2010), we investigate the efficiency of the QLD in a region close to the light cylinder surface.
2. For the considered physical parameters, it has been shown that the cyclotron instability appears for relatively low frequency range, producing radiation in the submillimeter/infrared domains. On the other

hand, despite the short cooling timescales, the effect of diffusion on particles recreates the pitch angles and produces the high energy radiation in the MeV-GeV bands.

3. The problem was studied versus three major magnetospheric parameters: the beam and the plasma component's Lorentz factors and the beam electrons' density. It was shown that the photon energy, ϵ_{MeV} , is a continuously increasing function of the beam Lorentz factor and the beam density. Contrary to this, by increasing the plasma component Lorentz factor, the corresponding photon energy decreases.

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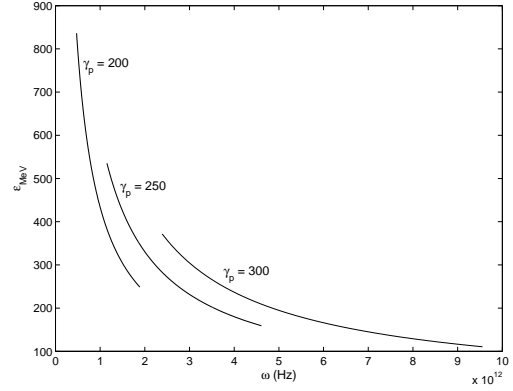


Fig. 3.— Behaviour of ϵ_{MeV} versus ω for different values of γ_p . The set of parameters is $L = 10^{45} \text{ erg/s}$, $\Omega = 3 \times 10^{-5} \text{ rad/s}$, $\gamma_p = \{200; 250; 300\}$ and $n_b = \{5; 10; 15\} \text{ cm}^{-3}$. The results show the strong connection of $\{100 - 800\} \text{ MeV}$ radiation with the emission in the frequency range $\{0.05 - 1\} \times 10^{13} \text{ Hz}$.